Chapter 10. R&D Programs and Related Studies

The purposes of Research and Development programs and engineering studies are to reduce technical risk and cost, and to improve performance. The following sections briefly discuss what we see now as the most important R&D that should be vigorously pursued for both Stage-1 and Stage-2. There is a distinct difference in the nature of the R&D between Stage-1 and Stage-2; the work on the low-energy collider emphasizes systems issues, engineering and cost reduction, while the R&D for the high-energy machine is strongly slanted toward the development of components. This difference is appropriate, because the components of the Stage-1 collider are relatively straightforward, whereas the Stage-2 machine requires cutting-edge components, particularly magnets.

10.1 R&D for the Stage-1 VLHC

Because of the simplicity of the magnet and accelerator systems of the Stage-1 collider, there are only a few risk-associated R&D studies needed. Most of the R&D effort is devoted to reducing costs.

10.1.1 Tunneling R&D and Engineering

The major cost driver in the Stage-1 collider is tunneling and other underground construction. Large investments in underground construction R&D and engineering studies are easily justified because even small improvements in efficiency will save considerable cost and avoid significant financial risks. Furthermore, the R&D results would be useful to a broad range of business and government far beyond high-energy physics. It might be possible to find funding from sources outside of HEP to support this R&D. The R&D is of two types: improvements in the current tunnel boring machine and conveyor belt muck removal systems, and trying new and innovative methods that might, if successful, reduce cost and improve safety.

Typically, forty percent or more of tunneling costs are in labor. Hence, development of automated or semi-automated procedures looks very promising. Such procedures could also result in improved safety, since fewer workers would be underground and at risk of injury. This is not fancy technology that will be difficult to develop and sell to the conservative tunneling industry, but relatively straightforward application of existing techniques that are widely used in other industries.

From a study carried out for Fermilab [1] cost drivers in conventional tunneling in Fermilab region geology are well understood. Improvement in tunnel boring machine (TBM) utilization can be achieved by fully instrumenting the TBM and trailing gear with pressure sensors, flow meters in the hydraulic and water systems, vibration sensors placed on all critical devices, and TV cameras positioned to watch all moving components. The TBM can be remotely operated from any place on the construction site. This dramatically reduces labor costs and improves job safety. Maintenance can be done as scheduled. Breakdowns aren't as costly, because you don't have large crews standing around waiting for a repair to be completed. The cost per meter of tunnel can be significantly reduced [2]. A Fermilab group has formed an informal collaboration with the Kenny Construction Company to instrument a TBM and gather its data in a TARP Tunnel under construction [3].

There are also many possibilities for the development of better tools and machinery to make tunneling faster, safer and cheaper. In a systematic R&D program aimed at reducing tunnel costs, new approaches to tunneling can be explored. A visionary goal is to have no people underground except during maintenance. The mining industry is moving toward totally robotic systems but this technological evolution has not yet reached the construction industry. A modified TBM with corner cutters [4, 5] will produce a flat floor and allow use of a diesel-fume free battery operated, rubber tired autonomous muck removal and transportation system.

Close collaboration between accelerator designers and tunnel engineers can also cut costs. The many additions, side caverns and adits that an accelerator requires drive up the cost of underground construction. Careful engineering of the accelerator in conjunction with the tunnel may be able to eliminate some of these and significantly reduce costs. This study will involve a multi-disciplinary team of accelerator scientists, engineers and underground construction experts.

10.1.2 Vacuum System

The vacuum system for the Stage-1 collider is a surprising cost driver. Development and studies of different methods to reduce its cost are worthwhile. These could include simpler and less costly ion pumps and improved beam-tube materials and fabrication techniques. There are a number of possibilities. There may be practical non-evaporable getter material (NEG) that will pump semi-inert gasses such as methane. It would also be worthwhile to investigate the possibility that NEG strips exposed to synchrotron radiation and/or secondary electrons can pump methane. If so, this would eliminate the need for ion pumps. Another fruitful area of investigation is thin film NEG coatings which are under development at CERN. At a minimum these could be useful in special regions of the machine where conventional pumping solutions are difficult or impossible. The possibility that these coatings could replace the NEG strips, and possibly eliminate the need for ion pumps when exposed to synchrotron radiation, should also be investigated. Photodesorption coefficients of thin film NEG coated beam tubes and the pumping speed of these coatings in the presence of synchrotron radiation need to be documented.

The possibility of using the already present cryogenics of the magnet transmission line for a beam tube cryopump was recognized at the beginning of the study but it was felt that the cost of the cold to warm transitions and thermal shields would exceed the cost of the system that was analyzed. Perhaps this question should be reexamined. Unless the cryopump temperature is equal to or less than ~3 K, cryosorber will need to be added to pump hydrogen beyond one monolayer.

10.1.3 Beam Stability

There are a number of potential beam stability issues in the Stage-1 collider. As discussed in Chapter 3, these have been solved in the design study by rebunching the beam in the Tevatron before injection into the collider, using a uniform filling sequence, and by using an audio frequency tune-equalization quadrupole in the Stage-1 collider. None of these steps seem difficult or expensive, but they do need to be studied, both on paper and by experiments on existing machines. In addition, there are some other promising possibilities, particularly TMCI feedback systems, that are even less costly and also deserve study.

Studies at Fermilab that might lead to reduced transverse beam emittance would allow lower current in the Stage-1 collider and have many good effects, including reducing the possibility of beam instabilities.

10.1.4 Magnetic Field Quality

Superferric magnets are unlikely to have many field-quality problems except near saturation. Nevertheless, we have not yet made a magnet with good field quality using the correct cross section for the design-study lattice. There is a contract with the D.V. Efremov Scientific Research Institute (St. Petersburg, Russia) to make two 6-meter long magnets with accurate laminations. It might be useful at the same time to build and test cross sections with some fast-turnaround fabrication method, such as wire EDM machining. A study of the sensitivity of the magnetic field to steel chemistry and production tolerances would also be informative and might lead to cost-savings. Many of these measurements have been carried out on the magnet test bench shown in Figure 10.1. In this apparatus, 10 turns of water-cooled conductor are used to emulate the 100 kA single-turn conductor in the Transmission Line magnet. It is a simple matter to make yokes of any desired pole shape and size, clamp them around the conductor, and make accurate measurements.

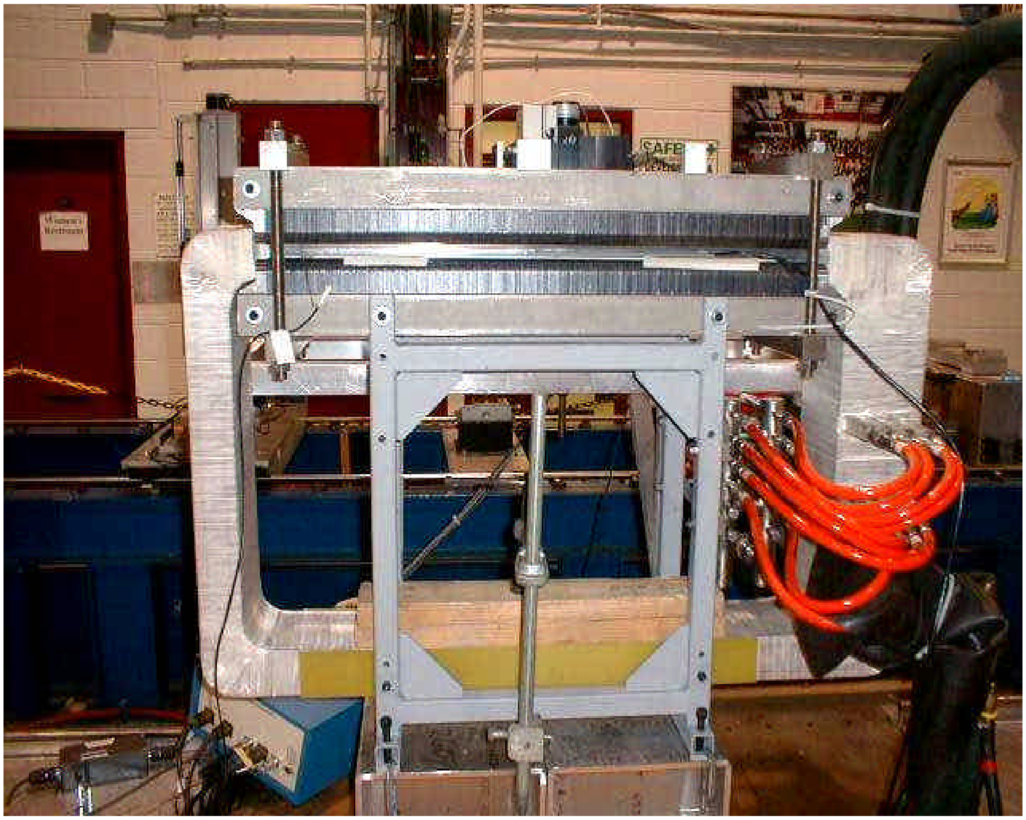

Figure 10.1. Apparatus for magnetic field quality measurements.

10.1.5 High-Gradient IR Quadrupoles

The interaction regions of the VLHC require high-gradient quadrupoles that seem feasible but are beyond the present state-of-the-art. These magnets need to be developed, and since such developments have traditionally taken many years, the R&D should start now. The target gradient for these magnets, 300 T/m, requires Nb_3Sn of improved performance, and hence, a superconducting materials R&D program is also required in parallel. The U.S. LHC collaboration has proposed developing quadrupoles of similar performance for a luminosity upgrade of the LHC. If that effort is funded, it may accomplish the necessary R&D for the VLHC as well.

Fermilab is particularly well-positioned to lead the high-gradient quadrupole R&D effort. In recent years, we have built the infrastructure necessary to do this work—reaction ovens, a strand-testing facility, a compact cable-making machine, winding and curing tooling for model and full-sized magnets, and a vertical dewar test facility (Figure 10.2) that will soon have 30 kA capability. In addition, if wide cables are required, LBNL is the world leader in cable-making R&D, and has a facility to make cables containing up to 60 strands. This infrastructure at the two labs allows the flexibility of design and fast turn-around necessary for a successful R&D program involving such challenging magnets.

Figure 10.2. The Vertical Magnet Test Facility with a model LHC IR quadrupole ready to be inserted for testing.

10.1.6 Magnet Production, Handling and Operation

The very long magnets discussed in the design study raise a number of issues that are certainly soluble but need both detailed engineering and some R&D. These include the welding of the half-cores from the inside to permit an open-gap magnet; design of the cryogenic pipes and support system for large thermal contractions; beam pipes and transmission lines with short or non-existent bellows; the use of thicker laminations, extruded steel yokes, and less costly low-carbon steel to reduce the cost of the steel yokes; and engineering and prototyping of handling, transportation and installation needs. The R&D plan must contain the fabrication and operation of long magnets in a "string test" that will prototype all of the issues involving the production, handling, installation and operation of the transmission-line magnets.

10.1.7 Cryogenic System

Figure 10.3 shows the apparatus used for developing the transmission line. The large magnet is used as the primary of a transformer to induce 100 kA in the single-turn superconducting transmission line. During the past 12 months several different transmission-line configurations were successfully tested in the current loop to 100 kA and beyond.

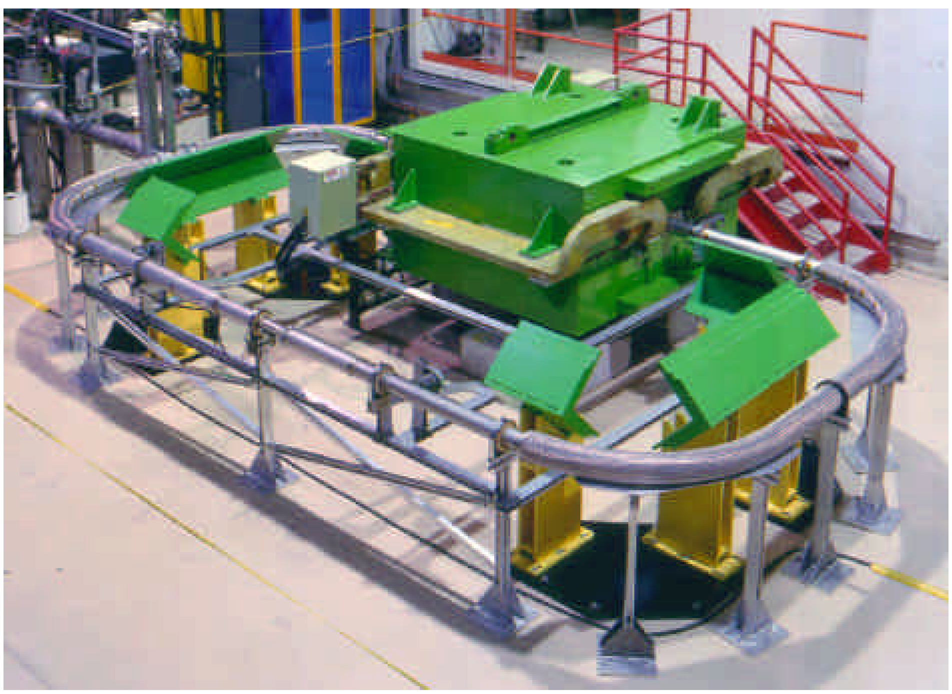

Figure 10.3. The test apparatus used at MW-9 for developing the transmission line.

The transmission-line magnet can, in principle, have a very small heat load, which leads to small cryogenic plants spaced far apart, and low operating costs. Several concepts exist for further optimization of this heat leak. With the plants spaced 40 km apart, there is the possibility of flow instabilities if there are regions of high relative heat load due to assembly errors or bad vacuum. These issues can only be understood and resolved by the combined use of computer simulation, bench-top laboratory experiments and large-scale demonstrations, using components fabricated in a realistic production environment. The results of these efforts will be fed back into the production and quality assurance methods, and will influence the designs of the instrumentation and controls systems, including software for stable control and recovery during upset conditions. The test string planned for operation at the MS-6 location at Fermilab will answer many of these questions. It will have magnets and transmission line mock-ups connected to a well-instrumented refrigerator close by. It is expected to be fully operational in mid-2002, although earlier tests will be done using helium from dewars.

Using turbo compressors could increase the efficiency of the cryogenic plant. In order to use turbo compressors, helium must be mixed with high molecular-weight gasses at the inlet of the machine and effectively separated at the outlet. It is necessary to develop a reliable separation/purification system to keep contamination of the helium below the required level.

As mentioned above, one of the issues of operating with supercritical helium is control of instabilities. One way to avoid these problems is to operate at higher temperature, in gaseous helium. It seems possible to add superconductor to the transmission line, which will have a small cost impact, permitting the transmission line to operate at a higher temperature. This would make control easier and the refrigerator more efficient, and may lead to a net cost reduction.

10.1.8 Public Acceptance and Outreach

One of the major hurdles that must be overcome before any big machine can be built is convincing the public that building and operating the collider under their homes and neighborhoods is both safe and environmentally sound. As a community, we have not been very adept at this activity in the past, but we will need to be in the future. A program of understanding the attitudes and real concerns of our neighbors and interacting with them in constructive ways must be started. In addition, understanding what other labs, such as CERN and DESY have done to permit them to construct off their sites would be useful.

Even though we believe the VLHC to be the least expensive way to advance the energy frontier, it is not cheap. Getting the public and political support necessary to be funded will be a very challenging task. It must begin by educating and informing American citizens and their leaders of the importance of this research to their culture, civilization and well-being. As a community, we need to lead in this effort and not leave it up to the funding agencies. Again, understanding what our citizens and leaders view as important and how we might fit in among those perceptions is the first step.

10.1.9 Other Engineering Studies

There are numerous issues for the construction and operation of the VLHC that can be solved by engineering studies that will not involve much R&D. In many cases, these are as important and challenging as the R&D itself. Among them are studies of the integration of construction and installation to reduce the total construction period. This is a complex organizational problem that could be studied through computer simulation. Other computer simulation studies might include construction and operational safety, which could inform us about the number of necessary egress points, the design of tunnel vehicles, and even safety and administrative practices.

Studies and simulations of beam accidents and their effect on the environment are absolutely necessary (see Section 5.3.6), as are studies of the environmental impacts of the actual construction of the underground and surface facilities. These studies must include the issue of groundwater handling and radiological contamination; for a detailed discussion, see Section 7.8.

The cost analysis presented in this study is very preliminary. It must be improved by continued iteration and deeper detail. In addition, there are other staging options and designs beside the one chosen for this study. It is important that some effort be invested early in the program to understand what the VLHC might look like and cost if those other designs were used. Exercises of this type must go hand-in-hand with discussions of high-energy physics goals and the politics of international collaboration and planning.

10.2 R&D for the Stage-2 VLHC

10.2.1 High Field Magnet R&D

The Stage-2 magnet system configuration with the vertical bore arrangement adopted in this study dictated the configuration of the superconducting magnets described in Section 6.1. Arc dipole magnets are based on the common coil design and react-and-wind fabrication technique. This is regarded at this time as the most innovative and cost effective approach, although it requires significant efforts to prove it experimentally. Extensive R&D efforts in this direction are in progress at Fermilab, LBNL and BNL.

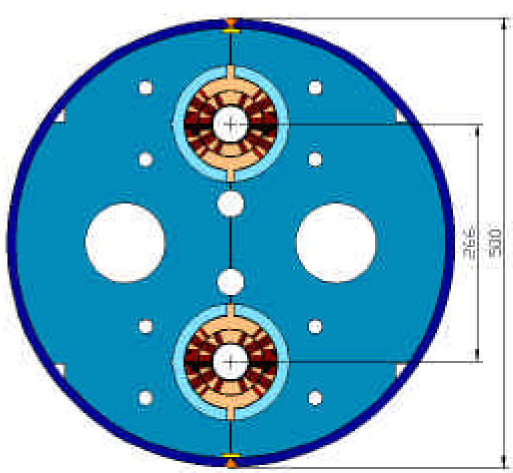

Figure 10.4. Cos-theta cold-warm yoke dipole with vertical bore arrangement. The yoke cold part is shown in the picture, the 15 mm thick yoke warm part with ID=680 mm is not shown.

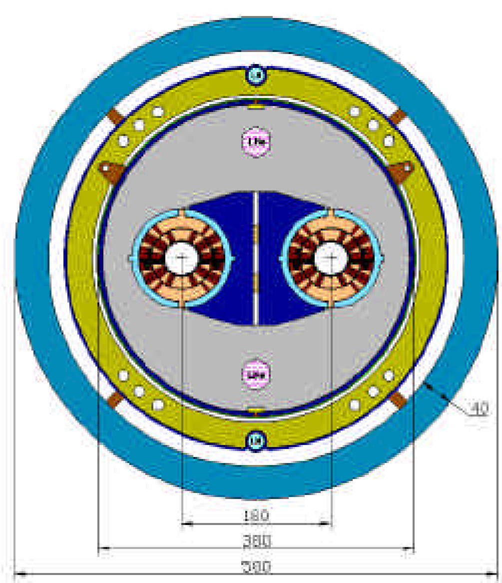

Figure 10.5. Cos-theta warm yoke dipole with minimized size and weight.

There are also other magnet design approaches based on the traditional cos-theta (shell-type) coil geometry which allows both horizontal and vertical bore arrangements as shown in Figure 10.4 and Figure 10.5. These magnets are being developed at Fermilab for the VLHC and meet the Stage-2 VLHC requirements, including operating field range, field quality, critical current and critical temperature margin, quench protection, etc. [6]. The designs and parameters of arc quadrupole magnets that match these dipole magnets are described in [7, 8].

Due to the small bending radii in the cos-theta type coils, we are forced to use the wind-and-react technique in order to avoid a large degradation of the cable critical current during coil winding. For the same coil bore diameter, the cos-theta coil configurations allow a reduction of the coil cross section area by about 20 percent with respect to the block-type coil. These coils can be placed much closer to each other, especially in the horizontal bore arrangement, reducing the iron yoke size and the total magnet size, weight and cost. The most straightforward design for the warm yoke [9] is shown in Figure 10.5.

The model magnet R&D programs carried out in several U.S. national labs and universities have to address the main question: which design approach and fabrication techniques are the best for Stage-2 VLHC? The Stage-2 magnet R&D program will consist of three traditional phases: Phase 1 - short model R&D; Phase 2 - full-scale prototype fabrication and tests; and Phase 3 - magnet string (half-cell) test. It will require funding at the level of $5 million-$10 million per year for five to 10 years to study different magnet designs and technologies, to select the best arc-magnet design, to fabricate and test a series of full-scale prototypes, to build and test a magnet system half-cell to demonstrate the feasibility of the Stage-2 magnet system. Results of this program will provide the basis for the cost estimate and schedule of the Stage-2 VLHC.

10.2.2 Strand and Cable R&D

To build the high field SC magnets with the required Stage-2 nominal field and gradient and reliable operational margins, the superconducting strands must provide certain parameters [10] discussed in Section 6.1 and summarized in Table 10.1.

Table 10.1. Strand target parameters for the Stage-2 high field magnets.

Parameter	**Value**
Strand diameter	0.300-1.000 mm
Critical current density J_c (4.2 K, 12 T)	>3000 A/mm^2
Effective filament diameter d_{eff}	<40 μm
Cu stabilizer	>50%
Residual resistivity ratio (RRR)	>100

Nb_3Sn is currently the most likely superconducting material for the Stage-2 high-field Superconducting magnets, because of its properties and commercial availability. At this time there are three technologies that may reach the desired technical goals: Internal Tin (IT), Modified Jelly Roll (MJR), and Powder-in-Tube (PIT). In the second half of 2000, a Superconductor R&D National Program for HEP applications was started by the DOE [11]. This program is focussed on reaching the conductor target parameters presented in Table 10.1 and on reducing Nb_3Sn strand cost. This program has proved remarkably successful. In only a few months of R&D, U.S. companies IGC and OST improved the critical current density of Nb_3Sn strands by 30%. Figure 10.6 shows the progress in time of Nb_3Sn strand critical current density since 1984. A trendline extrapolation suggests that reaching the goal of 3000 A/mm^2 is possible by the 2005.

The critical current density of Nb_3Sn strands is controlled by a few parameters, such as the volumetric fraction of the Nb_3Sn phase that can be packed in the non-copper part of a strand, the strand heat treatment procedure, and the flux-pinning mechanisms. All of these parameters are now under investigation and optimization [12-14] in order to reach the required J_c.

A critical parameter responsible for the persistent current effect in magnets and strand stability is the strand magnetization determined by $J_c \cdot d_{eff}$, where d_{eff} is an effective filament diameter. For the Nb_3Sn strands produced using the most cost effective technologies such as IT or MJR, d_{eff} is quite large about 100-120 μm, and only PIT provides a small d_{eff}, on the level of 50 μm, which significantly decreases the magnetization effects, but results in increased strand cost [15]. An optimization of the strand design and technology aimed at reducing d_{eff} in the high J_c Nb_3Sn strands is an important next step of the conductor R&D program.

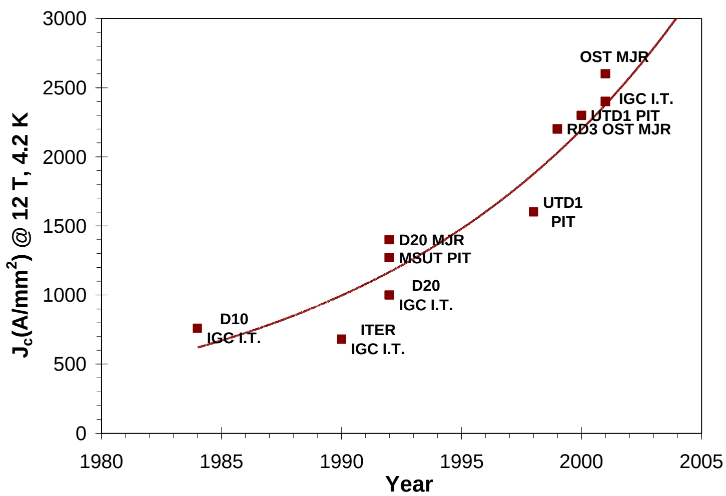

Figure 10.6. Improvement in J_c (4.2 K, 12 T) of Nb_3Sn since 1984.

It is necessary during magnet and cable fabrication and operation to reduce the critical current degradation relative to that of the original virgin strands due to strain as well as to control the interstrand resistance responsible for the thermal and electromagnetic coupling between the strands. In the wind-and-react technique, both strand plastic deformation during cabling (before reaction), and cable compression in the coil during magnet fabrication and operation (after reaction, due to coil pre-compression and Lorenz force) contribute to I_c degradation and interstrand resistive coupling. In the react-and-wind method, there is also I_c degradation due to the bending strain introduced during winding. The cable R&D program goals are summarized in Table 10.2. Cable studies performed at Fermilab and LBNL show significant progress in developing SC cable for accelerator magnets during last 1-2 years. The results obtained prove that cable R&D goals will be certainly achieved [16-19].

As was shown in section 6.1.8, the cost of Nb_3Sn strands is one of the major cost drivers of the Stage-2 magnet system. NbTi strands for accelerator magnets, thanks to previous HEP projects and the MRI magnet business, can be purchased in large quantities for about $100/kg. The small quantity price (e.g., 2 tons purchased for the U.S. LHC program) is as much as 50%

higher – about $150/kg. It is apparent that lower prices in the future for this conductor is unlikely to be realized, since most of the cost savings and property improvements available for NbTi have already been realized. The status of Nb_3Sn is in stark contrast to NbTi. The quantities being purchased annually are small at present (about 0.5 ton for accelerator magnets, two tons for MRI magnets, and two tons for fusion energy magnets). This factor of 100 lower volume means that the economies of scale available for NbTi do not exist. Consequently, at this time, Nb_3Sn conductor costs about $750/kg.

Table 10.2. Cable R&D goals.

Parameter	Value
Number of strands	28-60
Packing factor	87-90%
Cabling degradation	< 10 %
Bending degradation	< 10 %
Compression degradation	< 10 %
Strand crossover resistance	>10 µOhm

The goal of the HEP Conductor Development Program is to demonstrate that Nb_3Sn costs can be reduced to the $150/kg range when the production processes are scaled-up to those used for NbTi. In order to demonstrate this, the key is to scale up the unit process quantities, i.e. billet sizes, to the NbTi equivalent, and also to procure the raw materials in quantities that will show economies of scale. The necessary technological steps and the costs to do this, as well as the overall process costs are discussed in reference [20]. These scale-up efforts will require about $1 million per year for three years for each process that is selected for scale-up. However, the cost savings projected for a VLHC-size project will return this investment many times over, and may be the critical factor determining the feasibility of such a project.

10.2.3 IR Magnets for Flat Beam Optics

The parameters of various IR magnets required for the flat beam optics are given in Table 6-6. The layout is shown in Figure 3.10. The following are the major design considerations of these IR magnets:

- Small aperture (especially in quadrupoles for generating high gradients)
- Brittle superconductors that must be used for generating high field/gradient
- Large Lorentz forces (associated with high fields)
- Small separation between the two apertures (associated with the doublet optics)

Given the importance of these few magnets, state-of-the-art superconductors are used in the design. The ends of conventional cos-theta designs put a practical limit on the minimum aperture, particularly in quadrupole magnets made with brittle material. To overcome this and other limitations, Stage-2 VLHC IR doublets are based on non-traditional magnet designs with racetrack coils. These are conductor friendly designs with large bend radii and are suitable for containing large Lorentz forces.

The minimum separation between the two apertures in first quadrupole from the interaction point determines the layout of the entire interaction region and the maximum β-function for the given optics, since it sets the distance of that quadrupole from the IP. In addition, it also establishes the maximum pole-tip field of this and other magnets. In conventional 2-in-1 designs, the minimum separation is determined by the conductor width required for generating field gradient and the support structure required for containing large Lorentz forces. In the proposed design the amount of conductor between the two apertures is much smaller than on any other side and no support structure is required between the two apertures. This brings a large reduction in spacing (by about a factor of five) between the two apertures. The cross section of the proposed design is shown in Figure 10.7. In order to facilitate large bend radii, the return path of all turns is further away from the aperture. Field contours and field lines in the aperture of this magnet are shown on the right in Figure 10.7. The design is based on react-and-wind Nb_3Sn superconductor with a current density in the coil of 2500 A/mm^2 at 12 T. The magnets based on these design principles use a much larger amount of conductor than in a conventional design. However, the cost of conductor is not a major issue in designing a few critical high performance magnets.

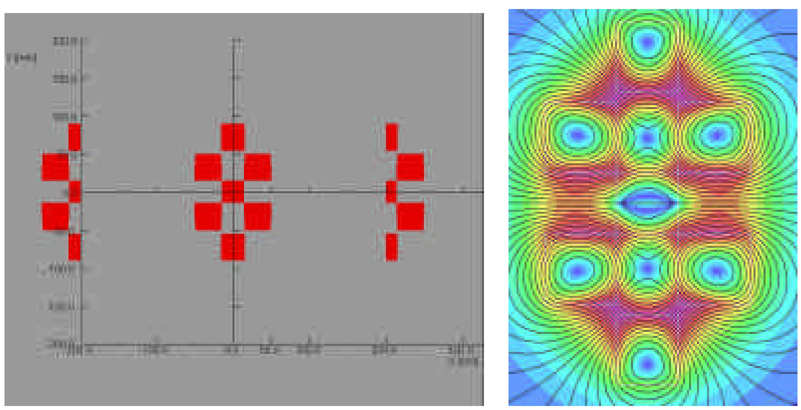

Figure 10.7. A conceptual design of 2-in-1 Q1A (left) and flux distribution in the coil region of the magnet (right). The design minimizes the spacing between two apertures.

This design also introduces a strong coupling and cross talk between the two apertures. The superimposition of a dipole field on the quadrupole coils increases the peak field in the conductor and reduces the maximum achievable gradient. The maximum gradient in Q1A (minimum separation) is, therefore, 400 T/m as compared to 600 T/m in Q1B, Q2A and Q2B where this effect is much smaller. The goal is to minimize the cross talk induced harmonics with the exception of the dipole field. By symmetry, the normal even harmonics and skew odd harmonics are theoretically zero. The target field harmonics will be obtained either by design or by correction. As the design evolves, the harmonics are expected to be reduced. All four quadrupoles will have a different cross section.

The VLHC IR region uses three types of dipole magnets. The design of the insertion region dipoles is also based on racetrack coils. D1A, D1B (one each on each side) are single aperture dipoles and D2 (two on each side) is a 2-in-1 dipole. The operating field in the smaller aperture (25 mm) dipole D1A is 16 T (quench field ~18 T) and it uses High Temperature Superconductor (BSCCO-2212) in a hybrid design. The operating field in the larger aperture

(50 mm) dipole D1B is reduced to 12 T to reduce the Lorentz forces in larger aperture. This field can be entirely obtained by Nb_3Sn superconductor.

10.2.4 Cryogenic-Related R&D for a High Field VLHC

The large total cryogenic system power, the magnet string lengths, total cold mass, and total helium inventory for a Stage-2 cryogenic system go well beyond that of previous systems. Scaling up standard cryogenic methods and systems to the size of a VLHC results in some new problems which call for R&D. The following is a list of possible areas for R&D in cryogenics for a high field VLHC.

1. It would be very desirable to reduce the installed cryogenic system power to significantly less than the presently estimated 105 MW. The heat load with the biggest potential for reduction by some innovative method is the synchrotron radiation load at 100 K. Developing methods for removing a fraction of the synchrotron radiation at room temperature could permit a dramatic reduction in cryogenic system size (both power and inventory) for a high-field VLHC.
2. Static heat load (thermal radiation and conduction) reduction might be possible. One should investigate the possible utilization of techniques developed for MRI or by NASA (e.g., trace cooling of supports and/or trace cooling of an inner shield). It could also be beneficial to fund a development effort toward better multilayer insulation (MLI) and MLI installation.
3. Improve cryogenic plant efficiency. Although there is no thermodynamic advantage in a heavier gas as a working fluid in a cycle, there might be some advantage of a higher molecular weight refrigerant (nitrogen or neon) in permitting the use of very large-scale air separation compressors and expanders. Hans Quack (cryogenics professor at University of Dresden, Germany) states [21]: “At a paper, which I am going to present at the CEC in Madison, I am going to propose a new system with a mixture of helium and neon as refrigerant. Such a refrigerant is nearly as efficient as helium, it allows power recovery of the turbines and a turbo compressor as main compressor and one can go down to 27 K.”
4. Improve helium screw compressor efficiency. This R&D item was listed at the Bloomington workshop in 1994 and the Jefferson Lab workshop in 1999. Quoting from the 1999 report [22]: “Screw compressor efficiency (FY94 recommendation): This one component accounts for more than half of total inefficiency of a refrigeration system. We use screw compressors rather than the more efficient reciprocating compressors because of their very high reliability. The root problem is that the He market is so small compared to Freon that it is difficult to get the vendor’s R&D attention.”
5. Another R&D item from the 1999 Jefferson Lab workshop which is also worth listing is a study of flow instabilities in long systems. Density wave instabilities could cause serious trouble for a VLHC, and a thorough understanding of this phenomenon would be required to ensure good design.

10.2.5 Synchrotron Radiation and Vacuum

Almost twenty years ago, when people started studying very high energy colliders like the SSC, the LHC and the Eloisotron, it was immediately recognized that the effect of synchrotron radiation on the beam tube vacuum and the cryogenic system would be a major issue and R&D challenge [23–26]. Numerous experiments and calculations have been done since that time, and they still remain major issues for the design and operation of high energy hadron colliders.

The cryogenic issues fall into two categories: removal of heat from the beam-tube liner, and the total heat load. These are complex but well understood cryogenic issues involving cryogen flow, thermal conductivity, pressure drop, and other parameters. So many parameters, in fact, that the solutions must be experimentally verified in addition to being simulated on computers. We anticipate, however, that these simulations of this complex system will be very useful in converging on a proper design.

The vacuum system is more difficult to understand, and must be experimentally verified. The usual solution proposed, but which will be tested first in the LHC approximately six years from now, is to have a beam-tube liner, shown in Figure 10.8, which intercepts the synchrotron radiation at elevated temperature (to take advantage of improved Carnot efficiency), and which has small perforations that permit gas to escape and be trapped, cryopumped and shadowed between the liner and the beam tube. This system must be tested at synchrotron light sources, although a lot will be learned during the early operation of the LHC. Among the issues are pumping speed, desorption coefficients and clean-up time.

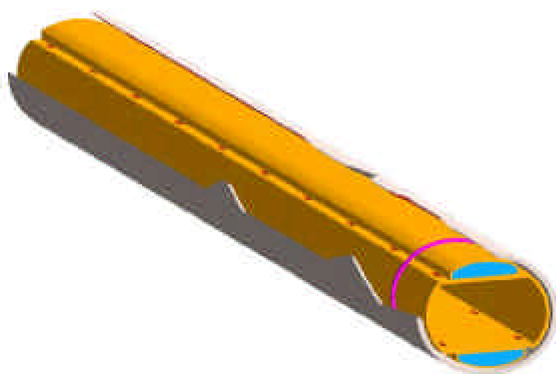

Figure 10.8. A model of the VLHC beam-tube liner.

A photon stop has been proposed as a possibility to intercept the intense synchrotron radiation in the Stage-2 VLHC [27]. The photon stop, shown in Figure 10.9, is a piece of metal or semiconductor that protrudes into the beam pipe between magnets, and intercepts all or most of the synchrotron radiation before it hits the beam-tube liner. The advantage of the photon stop is that it may be able to be operated at temperatures close to 300 K, thus saving significant amounts of cryogenic power, possibly more than 30 percent. A first pass engineering design of such a device has been completed [28]. The results of numerical impedance calculations [29] give additional support to the viability of the approach.

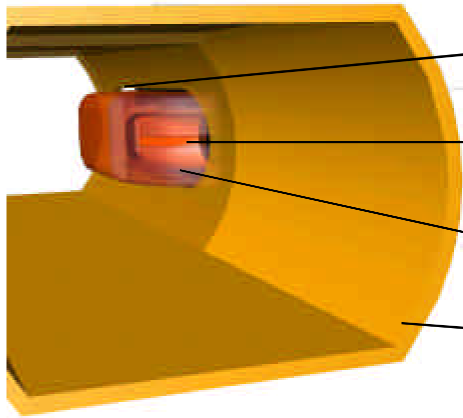

Figure 10.9. A model of a proposed VLHC photon stop, to be placed between magnets to absorb synchrotron radiation at 300 K.

An Argonne National Laboratory-Fermilab collaboration proposes a multi-step R&D plan towards the realization of such a device [30]. In the first step, a photon stop prototype would undergo tests in the Advanced Photon Source (APS) photon beam in a device that could be operated wholly at room temperature. Simultaneously, cryogenic tests of prototypes could take place at Fermilab. A photon beam is not required for such tests. Full-blown cryogenic and vacuum test series of the photon-stop in a VLHC-like setting is proposed as the final stage. An important part of the R&D is to understand the effect of the photon stops on the beam stability. This can be accomplished with a combination of sophisticated calculations and bench or beam measurements.

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